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Case Studies of Geophysical Search Methods Relevant to the Continuation Phase of an On-Site Inspection

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Abstract

Part II of the Protocol of the Comprehensive Test Ban Treaty prescribes the use of geophysical methods such as active seismic surveys and electrical conductivity measurements to search for and locate underground anomalies, including cavities and rubble zones, during the continuation phase of an on-site inspection. In this paper the application of spontaneous potential, magnetotelluric, active seismic, and gas sampling studies at the US Nevada Test Site associated with underground nuclear explosions will be described and discussed in the context of on-site inspections. Spontaneous potential and E-field ratio telluric methods were found to be effective in some geologic settings but not in others. An example of gas sampling is shown for which radiogenic gas was detected several years after detonation. The case study of the application of active seismic methods illustrates limitations imposed by the use of relatively simple systems in the field. Detection of a deeply-buried cavity or rubble zone will be difficult; results from the application of only a single method will likely be ambiguous. Best results will come from the synthesis of results from a number of widely-varying methods.

Introduction

The CTBT Protocol, Part II E, paragraphs 69-70 specifies inspection activities to be used up to the first 25 days of an on-site inspection. These activities focus on the task of narrowing the search area, presumably to one or more candidate areas no larger than a few tens of square kilometers. In this early phase of the investigation, techniques that emphasize large area reconnaissance (such as overflight) and short-lived phenomena (such as passive seismic and atmospheric gas and particulate monitoring) are specified. Once a continuation of the inspection has been approved in accordance with Article IV, paragraph 47, additional techniques, including active seismic and electrical methods, can be employed. These additional techniques are used to detect localized, but longer-lived phenomena associated with an underground nuclear explosion: the cavity and rubble zone and associated geophysical effects.

The purpose of this paper is to present case studies of electrical methods, gas sampling, and active seismic studies that have been employed at the US Nevada Test Site to look for the cavity or rubble zone of an underground nuclear explosion. All of these methods should be considered for use during the continuation phase of an on-site inspection under the CTBT. Each case study will be presented via the following format: 1) description of the survey method, including the physical anomaly to be searched for, 2) the geographical and geological setting of the study, 3) particular parameters of the survey, including time and personnel needed to complete the survey and process data, 4) results of the survey—i.e. to what extent the method was successful in detecting a cavity or rubble zone, 5) estimated applicability to other geographical and geological settings and possible environmental or logistical limitations of the technique.

Case Studies 1 and 2: Electrical Methods.

1. Spontaneous potential method

Spontaneous potential, also called self-potential (SP), anomalies are electrical fields occurring at the surface of the earth that can be detected by making relatively simple voltage measurements. The measurement method is passive, i.e. no active energy sources are employed. SP anomalies are commonly used in surveying for zones of fluid seepage, mineral deposits, or geothermal systems and are most effective when there is subsurface flow of heat and/or fluid, both of which may be factors associated with an underground nuclear explosion. The measurements are easy to make, but can be difficult to interpret. Best success occurs where the subsurface geology is not complex.

SP measurements are carried out by measuring the voltage between two non-polarizing electrodes which are placed in soil on the surface of the ground, as shown in Fig. 1. For a survey, a central location is chosen as a reference point and all voltage measurements are referenced to that one location. The most difficult aspect of the measurement is that it is necessary to string a wire between the reference electrode and the measurement point; this means that for a survey 2 km long, a wire must be strung from the reference electrode 2 km to the last measurement point. Measurements are made with a high impedance (10 megohms) voltmeter (hand-held, battery-powered models are available). The type of electrodes used commonly are copper-copper sulfate porous electrodes (Fig. 1) that make a non-polarizing, low-resistance contact with soil. (Good low resistance contacts with bare rock are more difficult to obtain). The connecting wire between the electrodes is high gauge (small diameter) and insulated; there is a trade-off between smaller wire (less weight to carry a spool to the farthest electrode) and wire strength. Measurement locations must be surveyed or determined with a GPS system to an accuracy of about 5 meters. SP measurements can be made to an accuracy of 5 mV; background noise is generally on the order of 10 mV. Anomalies in geothermal fields can range in amplitude from 50 to 2000 mV (1).

The case study discussed here (see ref. 1) concerns 7 separate sites at the US Nevada Test Site. Six of the surveys were done within 2 years after detonation of an underground nuclear test. On one of the sites, surveys were done before and after the detonation. The underground explosions associated with the sampled sites had depth of burial (DOB) ranging from 147 m below static water level (SWL) to 316 m above SWL; yields ranged from a few kilotons to greater than 100 kt. All the surveys were done in Yucca Flat; the geology there is thick alluvium and tuff overlying Paleozoic carbonate bedrock which occurs at depths ranging up to 650 m or more.

The SP survey lines at each site were carried out along 5-6 radial profiles 960 - 2680 m long, with measurements made every 100 m. An example of measurement results in the vicinity of emplacement hole U3mh is shown in Fig. 2. Note the general “sombrero” pattern of a central low and outer high potential that then drops back down with distance from the center. Local anomalies on the order of -180 mV or lower were seen within 30 m of well casings; these are not shown on the figure. The anomaly shown in Fig. 2 is typical; the anomaly patterns observed ranged from ±20 to ±80 mV in magnitude over a background of ±10 mV. Most of the anomalies were still detectable 100-500 days after the explosion; one anomaly was observed to still be present 25 years after an earlier survey. Note also that the central low zone of the anomaly pattern was often offset from surface ground zero of the detonation. The cause of this is unknown, but could be related to regional ground water flow.

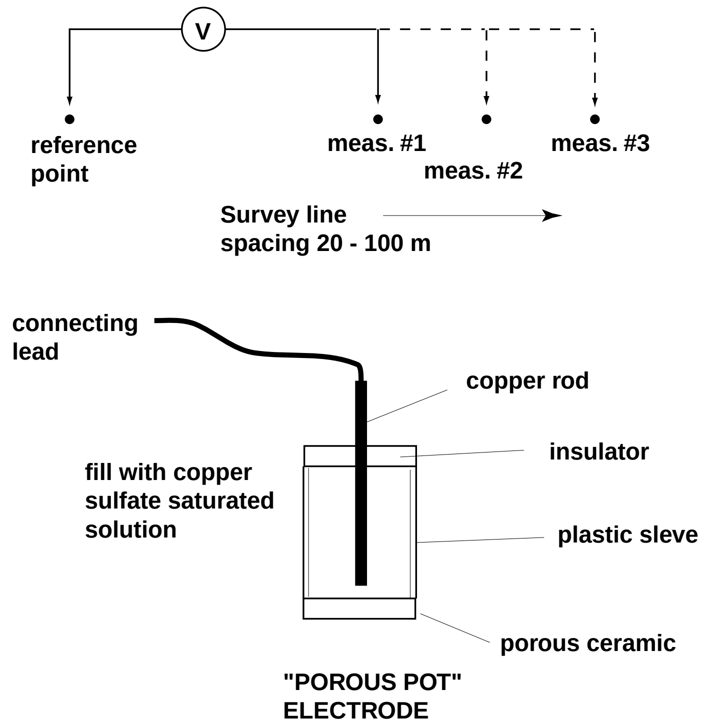

Figure 1. Layout and electrodes used in an SP survey. The upper diagram shows how voltage measurements are taken along a survey line. Voltage is measured from the reference electrode (which is not moved) to a successive series of measurement locations along the line. Measurement spacing does not have to be uniform. The lower diagram shows the configuration of a typical commercially-available porous electrode.

At well location U4au in Yucca Flat, the detonation depth was 87 m below SWL. The chimney did not collapse to the surface, but extended upwards about 150 m (~ 70 m above SWL). An SP anomaly was not observed one day after the test, but one appeared on a survey taken one month later. This anomaly was still present 5.2 years later.

The cause of these anomalies is presumed to be fluid or heat flow across a subsurface boundary or discontinuity. The rubble zone effectively acts as a zone of high electrical resistivity; other boundaries could be resistivity contrasts related to changing geology or the static water level (which marks the zone of saturation and lower resistivity). Fig. 3 shows a theoretical analysis for a heat anomaly which crosses a horizontal boundary. The strength of the anomaly depends on the radius of the high temperature zone, the depth of the detonation and the resistivity contrast over the horizontal boundary. Time-dependent models which included heat conduction-thermoelectric effects due to a chimney rubble zone were used to model SP anomalies similar to those of Fig.2. A thermal zone of finite extent (25 m radius) at steam temperature with resistivity constrasts of 5:1 between rubble and surrounding rock were sufficient to produce a realistic model anomaly with time evolution similar to that observed.

SP measurements are relatively easy field measurements to obtain. The equipment is simple, rugged and portable. A two-person team on foot in desert terrain should be able to survey 2-4 km of profile line per day in good weather. Thus this technique should prove to be a valuable local survey tool for narrowing the search area during the continuation phase. Measurements will be more difficult to carry out in rugged terrain, where bedrock is ubiquitous (e.g. glaciated terrain or

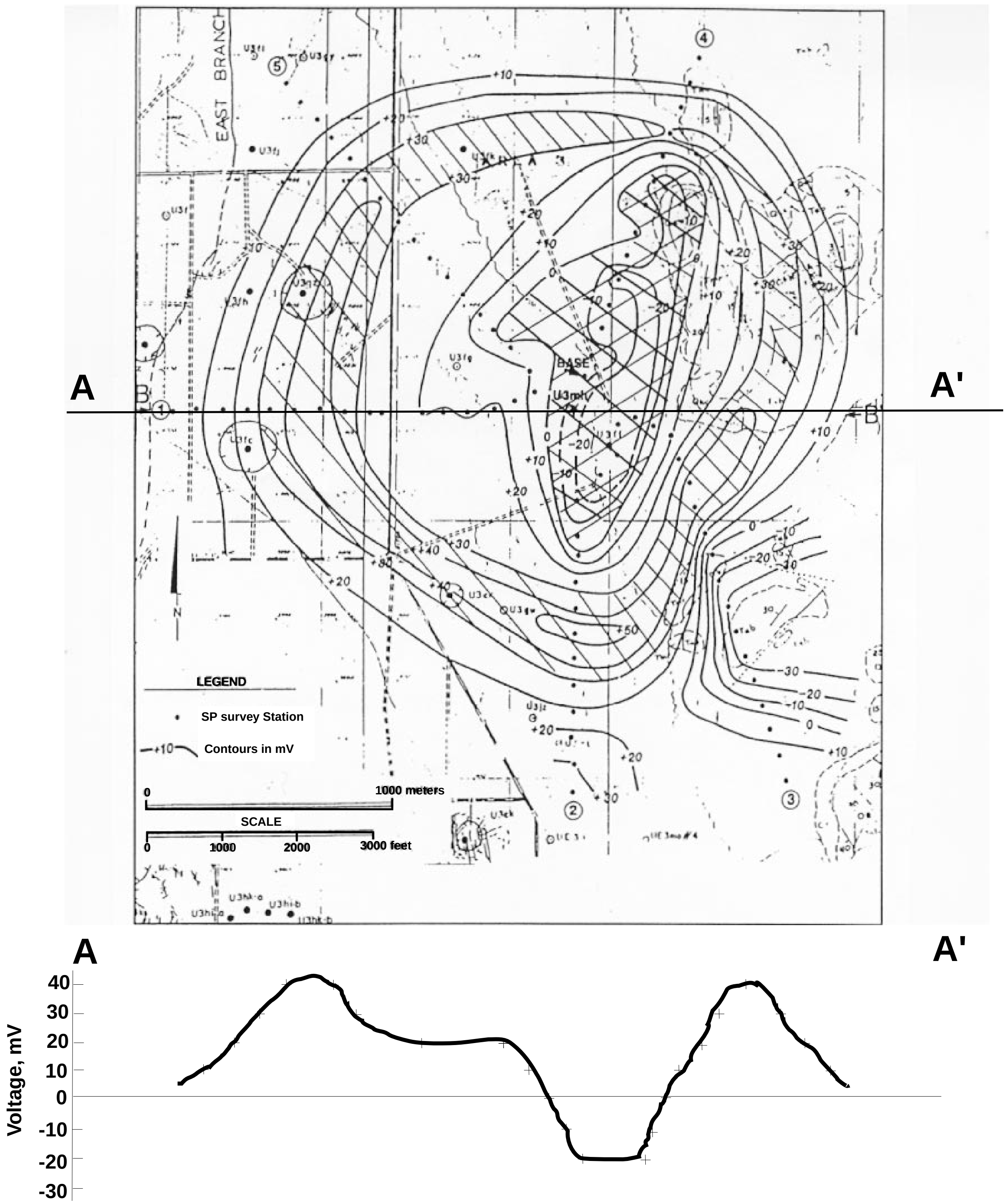

Figure 2. Upper diagram shows SP data taken at Yucca Flat; contour intervals are 10 mV (figure taken from ref. 1). The cross-hatched area highlights high and low extremes of the measurements, which are also shown in the profile at the bottom.

Sierra-Nevada granitic terrain), or highly vegetated areas. Measurements should not be carried out during rain storms or during snow melt, since flowing water or saturated conditions may affect background noise. Freezing conditions can create difficulties with the use of electrodes that employ liquids, but most of these limitations can be overcome except for severe cases. The biggest challenge to the interpretation of SP data comes from complexities arising from heterogeneous geology, overlapping explosion sites (as may occur in a test area), and the multiplicity of driving functions (heat and pressure from the explosion versus regional fluid flow). SP surveys in another geologic setting (Rainier Mesa, welded tuff geology), although not as comprehensive as these, came up with less positive results (2).

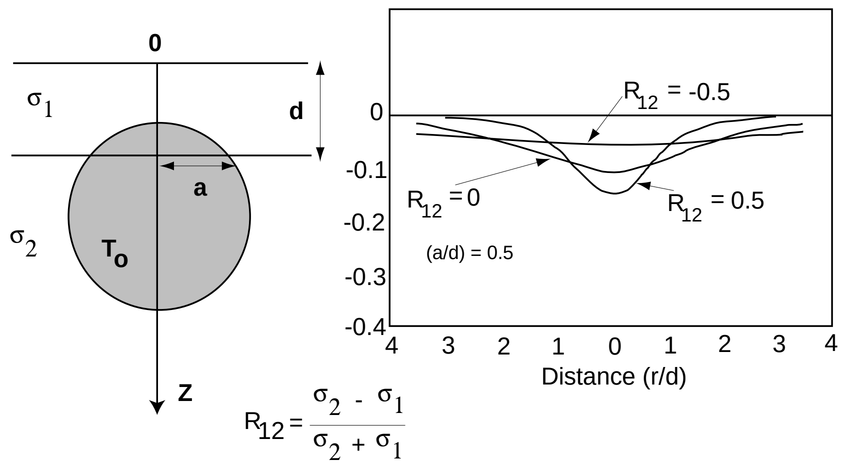

Figure 3. On the left is a conceptual model used to simulate SP signals from underground nuclear explosions. A high-temperature sphere overlaps a resistivity boundary at depth d in a circle with radius a. On the right is the anticipated SP profile as a function of the resistivity contrast, represented by R12, and the ratio of a to d. Note that the strength of the anomaly depends on the depth to the cavity; the strongest anomaly occurs when the lowest layer is more resistive.

2. E-field-ratio telluric method

The E-field-ratio telluric method is another passive electrical survey method for detecting lateral variations in subsurface electrical conductivity. The technique utilizes naturally occurring time-varying currents induced in the earth by ionospheric and tropospheric electromagnetic activity. As in the case of SP measurements, the equipment is rugged, portable, and available commercially. Survey lines several kilometers long can be completed by a two-person team in a day and, with modern equipment, data analysis has been highly automated.

The E-field-ratio telluric method has been extensively used as a reconnaissance tool in geophysical exploration, mainly for looking at variations in electrical conductivity at depths of many kilometers. Depth of investigation depends on the frequencies monitored; thus by confining the survey to higher frequencies, variation of conductivity at shallower depths can be considered. A survey is carried out by placing 4 electrodes in the ground along the line of the survey (see Fig. 4) with connecting wires to form a dipole pair. Voltages are read separately and simultaneously from each leg of the dipole. The ratio of the two voltages is related to the conductivity structure of the rock beneath the lines; if there is a conductivity change between two adjacent measurement locations the voltage ratio will change. Thus a survey is carried out along a line by overlapping dipole segments and recording changing voltage ratios referenced to the starting point (see Fig. 4). Thus a lateral change in the conductivity structure below a dipole location will show up as a change in the E-field ratio. By taking the ratio in different frequency bands the depth where the conductivity change takes place can be estimated; lower frequencies are most affected by deep-seated changes, higher frequencies by shallower changes. The optimum frequency to observe effects at 300 m depth is about 100 Hz.

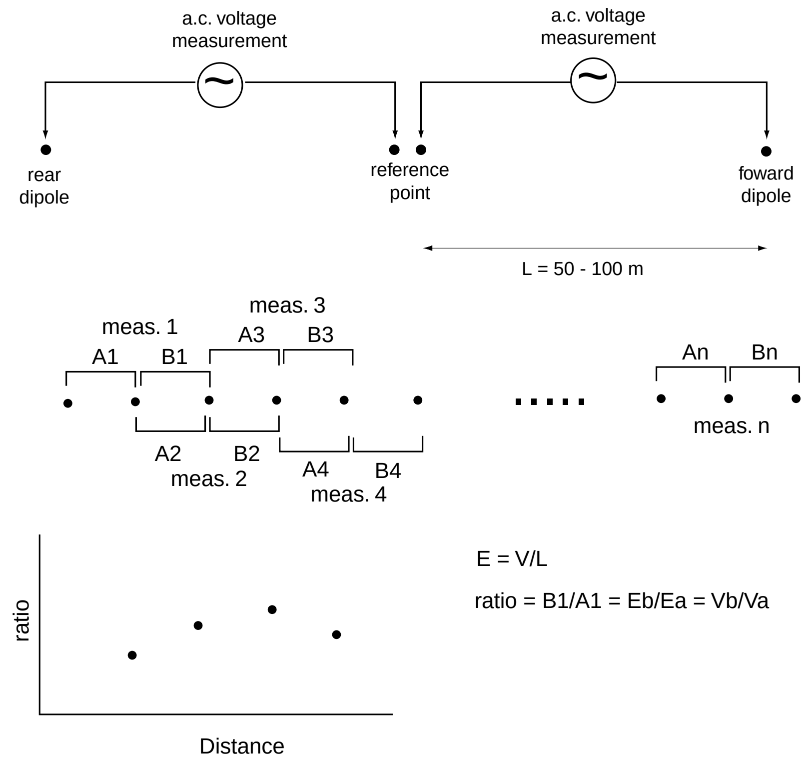

Figure 4. Top diagram shows layout of an E-field-ratio telluric survey. Variable voltages are measured over a forward and rear dipole measurement pair. The same type of electrode is used as shown in Fig. 1. The middle diagram shows how pairs of measurements are “leapfrogged” along a survey line; for measurement 2, the rear dipole is moved to the former forward dipole position and the forward dipole is moved to the next set of electrodes. The bottom chart shows how the measurements are plotted. Voltage measurements are made over a selected frequency band; the signal amplitude ratio is determined for waveforms on both dipoles that have high temporal correlation.

This case study concerns two E-field-ratio survey lines that were carried out over underground nuclear tests at the US Nevada Test Site in the early 1980s (4). Both surveys were done over tests done in Yucca Flat above SWL for which a collapse rubble zone was assumed to have come within 100 m of the surface. The rock type is thick alluvium overlying tuff. The frequency range of the observations was 0.05 Hz to 125 Hz in several separate bands. Best results were seen, as expected, at the higher frequencies; the 8 Hz and 100-125 Hz bands. An anomaly pattern at the highest frequencies revealed a well-defined circular pattern which, as is also seen from some of the SP surveys, was offset laterally from surface ground zero of the explosion (Fig. 5). It is important as a consistency check to run the survey at a variety of frequencies because variations seen at lower frequencies are influenced by shallow-based effects. Estimates of the depth to the features causing anomalies can be improved with better knowledge of subsurface resistivity; once an anomaly is detected, a controlled-source electrical survey can be employed to gain more information. Similar E-field-ratio results to those at Yucca Flat were obtained on Rainier Mesa using somewhat lower frequencies (see reference 2).

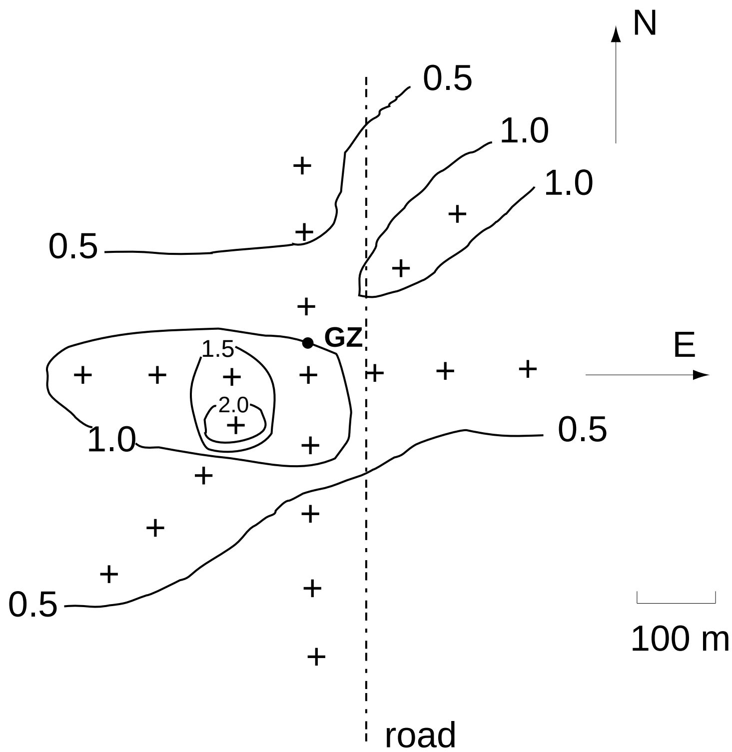

Figure 5. E-field-ratio data from Yucca Flat. GZ marks surface ground zero of an underground nuclear test. Measurement locations (see Fig. 4) are marked with a cross. Contours are in intervals of a 0.5 E-field ratio. A high ratio indicates a more resistive area beneath the survey point. Note that the anomaly is offset from GZ.

For application to the continuation phase of an OSI, this method is attractive because it is quick, portable, and a large area can be surveyed in a relatively short time. Many of the limitations described above for SP measurements apply to telluric methods. Geological complexity is probably the most severe factor. In addition, measurements must be made in daylight hours because that is when the telluric source currents are strongest. There is also a trade-off between the length of the dipole lines used (50 - 100 m is typical) and resolution; since the dipoles of successive measurements must overlap, the minimum measurement spacing is limited by signal strength to 50 - 100 m. A repeat measurement, with measurement points offset from the first line, can be used to get better resolution of an anomaly. A wide variety of telluric equipment is commercially available with digital processor-based analysis enhancements.

Case Study 3: Gas Sampling

Except for drilling into the explosion cavity and finding radioisotopes, detection of radioactive isotopes of Xe and Ar gas would be the most definitive piece of evidence in an OSI pointing to a violation of the CTBT. Thus gas sampling is one of the most important activities of an OSI. This case study, based on measurements carried out on Pahute Mesa at the US Nevada Test Site (4), serves to illustrate actual experience with gas sampling and important aspects of gas dynamics associated with underground nuclear testing.

The purpose of the study, carried out in 1991, was try to determine if gas escaping from an underground explosion cavity was driven by internal cavity pressure or by barometric pumping. The explosion cavity investigated was created by an underground nuclear test carried out in 1984, which occurred at a depth of about 640 m in fractured, bedded tuff. The rubble chimney extended upward to about 320 m depth (see Fig. 6). In the experiment, two different non-radioactive, inert tracer gases were mixed with air that was then pumped into the cavity. Several million cubic feet of the gas-tracer mixture were pumped into the cavity, but none of the tracer gases were detected at the surface along a prominent fracture (Fig. 6). The interpretation of this result was that a lateral high-permeability pathways allowed the air to preferentially move laterally rather than vertically and thus none of the tracer gases made their way to the surface.

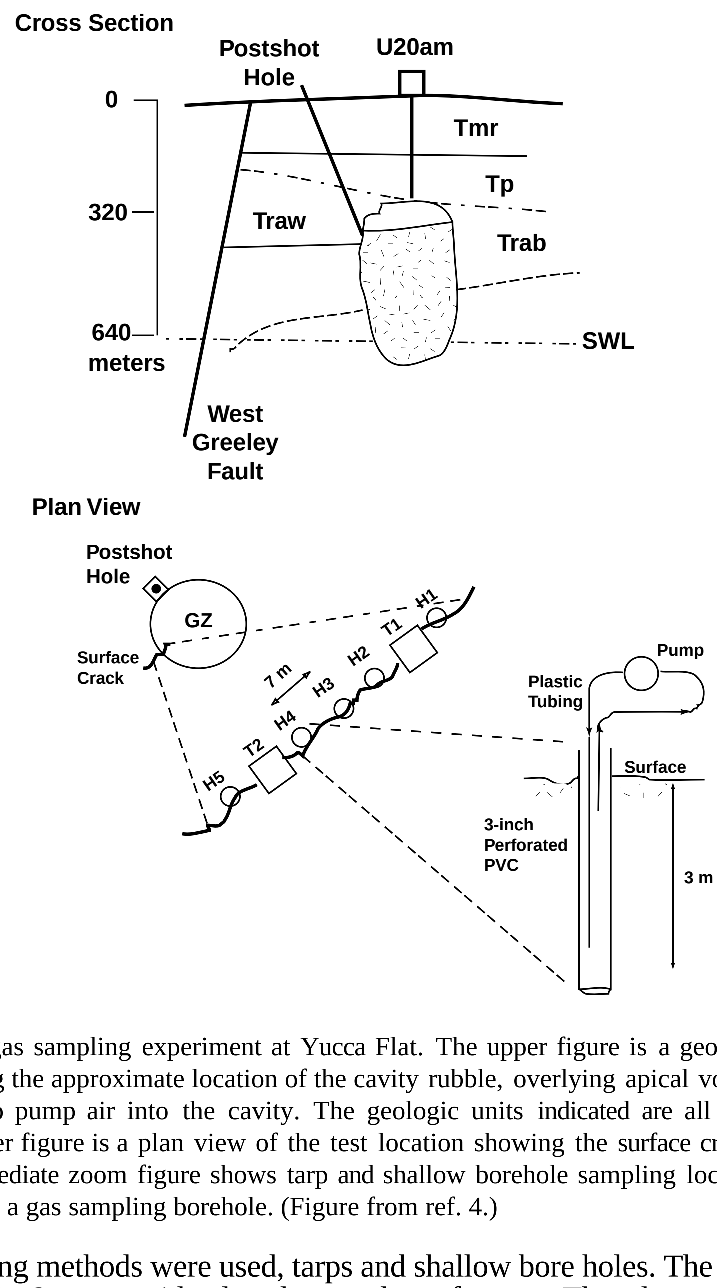

Figure 6. Layout of gas sampling experiment at Yucca Flat. The upper figure is a geologic cross-section of the nuclear test site showing the approximate location of the cavity rubble, overlying apical void, and the configuration of the bore hole used to pump air into the cavity. The geologic units indicated are all members of the Timber Mountain tuff. The lower figure is a plan view of the test location showing the surface crack that was sampled for tracer gases. The intermediate zoom figure shows tarp and shallow borehole sampling locations. The largest zoom figure shows a layout of a gas sampling borehole. (Figure from ref. 4.)

Two types of sampling methods were used, tarps and shallow bore holes. The tarps consisted of plastic sheets about 2 - 3 m on a side placed over a large fracture. The edges of the tarps were held down with soil and rocks. Five holes near the fracture were drilled to a depth of 3 meters and cased with 7.6 cm diameter PVC pipe with perforations in its lower half. Annular space around the casing was filled with twisted plastic sheeting and covered with soil. The casing was capped and fitted with pass-through holes for 0.63 cm diameter tubing for circulation of air through the air space in the top of the capped borehole. Gas samples were taken from the tarps by piercing a hypodermic syringe through the tarp. Samples from the bore holes were taken by inserting a hypodermic syringe into a rubber septum located on the outer side of the air circulation pump. An electron-capture gas chromatograph was used to measure tracer gas concentrations.

When sampling was done 1-2 months after the air injection, during a period of falling barometric pressure, the trace gases, as well as residual krypton gas from the nuclear products, were detected. The researchers estimated that about 5% of the cavity gases were released per year via barometric pumping and that surface concentrations of gas were on the order of 1000 times lower than those expected to exist within the cavity and chimney rubble. During a low pressure excursion, a series of gas samples were taken at locations away from the fracture, around the perimeter fence of the site (large circle of lower part of Fig. 6), by merely inserting the syringe into the soil. Some of these samples yielded as much tracer gas as one of the tarp sites sitting on the fracture. Apparently, these additional sampling sites occur over fractures buried under shallow alluvium. This is important, because it implies that the most obvious sampling sites (faults and fractures visible on the surface) may not be the only places were barometrically-driven gases can be detected.

Most notable for the purpose of an OSI were observations related to the two sampling procedures. Tracer gases were only detected at the tarp sites during periods of falling barometric pressure; apparently the gas is pushed back into the fracture and wall rock during rising pressure and barometric highs. The capped collection holes produced tracer gases even during periods of rising barometric pressure; apparently they retain a longer memory of the tracers because the holes have contact with the less mobile gases residing within the rock matrix. The lesson here is that both types of sampling methods should be considered for the continuation phase of an OSI. Another important lesson is that it may take a month or more for cavity gases to reach the surface via barometric pumping. Because complete knowledge of the subsurface rock properties and nature of fractures can never be completely known, it will be virtually impossible to predict when or where cavity gas may reach the surface. This factor poses a problem for evaders, but is not necessarily a problem for inspectors.

Case 4: Seismic reflection surveys

Many different types of seismic surveys have been carried out at the US Nevada Test (5, 6, 7, 8, 9). The bulk of these have been reflection surveys aimed at detection of the Paleozoic (PZ) basement rocks which underly younger alluvium and tuff at depths of up to 650 m or more. Very early in the investigations, it was realized that getting enough seismic energy into the ground was the biggest problem; the alluvium and tuff absorb seismic energy and it is difficult to propagate high frequencies, thus limiting the ultimate resolution of the surveys. However, with carefully designed surveys data was obtained that produced useful profiles of PZ depths and the configuration of the basement rocks.

LLNL experience with refraction surveys was typically as follows (N. Burkhard, personal communication). Seismic reflection lines (2-D survey) were done using 2.3 kg of explosive as a source with shot points every 15 - 25 m. To carry out the seismic survey, on lines where the shot and sensor positions had been previously surveyed, a crew of 20 could do about 100 shot points a day. Thus it took 4 - 5 days to run an 8 km survey line. These lines generally produced good profiles of the PZ basement and resolved one or two other velocity contrasts in the overlying sediments (such as the tuff/alluvium boundary); none of the lines were run closer than 100-200 m from surface ground zero of underground test sites. Besides lack of high frequency energy, lateral heterogeneity of the geology had the largest (negative) effect on resolution; resolution was not sufficient to detect an underground cavity.

About 10-15 years ago, Los Alamos National Laboratory carried out small-scale reflection surveys over three underground nuclear explosions that did not collapse to the surface and were known to have subsurface rubble zones with cavities near the top (Alan Cogbill, personal communication).

One survey took place in Yucca Flat (alluvium and tuff over PZ), one was conducted on Rainier Mesa (tuff, both welded and vitric), and one was conducted over granite. Lines were run with a small group interval (1-2 meters) with a maximum line length of 300 m. Only one line was run over each site, which took a 4-person crew several days to accomplish.

Even though the crew knew fairly precisely where to survey for the rubble zone and cavity, the surveys were unable to detect the target. The primary limitation was attenuation of high frequency energy in the tuff and alluvium. For the granite site, the investigators thought that there was some evidence of a void in the records, but the data were equivocal. The Rainier Mesa case that was not detected involved a known, hemispherical cavity 9 m in diameter and 113 m deep.

Additional experience by Los Alamos National Laboratory (5, 7) showed that surveys which employ a surface vibroseis source with downhole seismic instruments (called a surface to borehole survey) may be more productive for detecting subsurface cavities; but then a properly placed borehole is needed, which may be problematic in an OSI context. Such an approach was tried by Majer et al. (9) on Rainier Mesa associated with the US Non-Proliferation Experiment (NPE) but in that case voids were not a target of search. In the study by Carroll (8), re-entry holes near tunnel explosions on Rainier Mesa were used to study the effect of the rubble and fracture zone on local seismic velocities. Carroll found that shear velocities were significantly affected over a much larger volume than were compressional velocities. The implications of this are that a seismic survey that incorporates shear velocities to locate an underground cavity (although more difficult to carry out) may meet with better success.

The main point to made with these case studies of active seismic methods is this: detection of an underground cavity from an explosion can be very difficult, even when considerable resources are brought to bear. In another US paper at this OSI workshop, Dr. Al Smith will discuss modern methods of active seismic surveys and options available for application to an OSI.

Summary

Case studies of two passive electrical methods, spontaneous potential and E-field-ratio tellurics, show that these methods can be quite useful in an OSI context. The methods can be easy to deploy and carry out in the field, depending on vegetation and terrain, and can provide clear indication of the effects of an underground explosion when the geology is not complex.

Gas sampling experience at the US Nevada Test Site from one underground nuclear test cavity site demonstrates the importance of barometric pumping for moving gases from the cavity to the surface. Both tarps and shallow boreholes were shown to be effective for gas collection and sampling. Where and when gas will arrive at the surface is unpredictable because of the many factors involved; it may take a month or more for gas to reach the surface.

Experience with active seismic methods at the Nevada Test Site shows that where geology highly attenuates seismic energy it can be very difficult to image the subsurface at resolution levels needed to detect an explosion cavity. Special techniques and highly efficient energy sources will have to be employed in order to search for explosion cavities in such terrain.

REFERENCES

1. McKague, H. L., E. Kansa, P. W. Kasameyer, R. F. Corwin, 1991, Detecting and Modeling Persistent Self-Potential Anomalies from Underground Nuclear Explosions at the Nevada Test Site, C. W. Olsen, ed., Proceedings of the Sixth Symposium on Containment of Underground Nuclear Explosions, Vol. 1, Reno, NV, September 24-27, 1991, US DOE report CONF-9109114-Vol. 1, pp. 159-174.

2. Sweeney, J. J., 1994, Spontaneous potential and telluric measurements on Rainier Mesa related to the NPE, M. D. Denny, ed., Proceedings of the Symposium on The Non-Proliferation Experiment (NPE): Results and Implications for Test Ban Treaties, Rockville, MD, April 19-21, 1994, US DOE report CONF-9404100, pp. 8-41 to 8-50.

3. Didwall, E. M., and M. J. Wilt, 1983, E-Field-Ratio Telluric Techniques Applied to Cavity Detection for OSI Operations, Lawrence Livermore National Laboratory report UCID-19780, 26 pp.

4. Nilson, R. H., P. L. Lagus, W. B. McKinnis, J. R. Hearst, N. R. Burkhard, C. F. Smith, 1991, Field measurements of tracer gas transport induced by barometric pumping, C. W. Olsen, ed., Proceedings of the Sixth Symposium on Containment of Underground Nuclear Explosions, Vol. 1, Reno, NV, September 24-27, 1991, US DOE report CONF-9109114-Vol. 1, pp. 359-375.

5. App, F. N., W. R. Meadows, A. H. Cogbill, 1983, Mapping of Paleozoic structure in north-central Area 7 of the Nevada Test Site -- A Geophysical Case History, Los Alamos National Lab report LA-UR-83-2266. 27 pages.

6. Burkhard, N. R., 1983, NTS Seismic reflection data and the problems thereof, Proceedings of the Monterey Containment Symposium, B. C. Hudson et al., eds., Monterey CA, August 26-28, 1981, Los Alamos National Laboratory Report LA-9211-C, Vol. 1, pp. 339-341.

7. App, F. N., 1983, Progress in seismic exploration at Los Alamos, Proceedings of the Monterey Containment Symposium, B. C. Hudson et al., eds., Monterey CA, August 26-28, 1981, Los Alamos National Laboratory Report LA-9211-C, Vol. 1, pp. 343-353.

8. Carroll, B. D., 1983, Seismic velocity and postshot properties in and near chimneys, Proceedings of the Monterey Containment Symposium, B. C. Hudson et al., eds., Monterey CA, August 26-28, 1981, Los Alamos National Laboratory Report LA-9211-C, Vol. 1, pp. 379-396.

9. Majer, E. L., L. R. Johnson, E. K. Karageorgi, and J. E. Peterson, 1994, High resolution seismic imaging of Rainier Mesa using surface reflection and surface to tunnel tomography, in M. D. Denny, ed., Proceedings of the Symposium on the Non-Proliferation Experiment (NPE): Results and Implications for Test Ban Treaties, US DOE CONF-9494100, pp. 5-15 to 5-20.

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